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Progress Report
Office of Naval Research

Single Electron Capacitance Spectroscopy

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Awards received by Principal Investigator since this contract was issued:

National Science Foundation, Young Investigator Award (1993)
The David and Lucille Packard Foundation, Packard Fellowship (1993)
The Alfred P. Sloan Foundation, Alfred P. Sloan Fellowship (1994)
Univ. of Illinois Foundation, The William L. MacMillan Award (1994)

Goals and Objectives:

Three years ago, we developed "Single-Electron Capacitance Spectroscopy" (SECS). This is a means for measuring the quantum energy levels of nanoscale objects such as quantum dots, single impurity atoms, and localized electronic states in a semiconductor. The resolution of the method is limited only by the sample temperature, and objects containing as few as one electron may be probed. We intend to develop this type of single electron spectroscopy into a general tool for studying nanostructured materials.

Since May of 1993, when this ONR contract was awarded, we have largely constructed the low temperature and processing facilities required for these experiments. In this regard, we have completed installation of a top-loading dilution refrigerator with a 16 Tesla integral magnet, a helium-3 refrigerator, an electron beam lithography system, and a scanning tunneling microscope controller. Several new physics results are presently being explored.

Additionally, one project described in our ASSERT proposal has lead to an entirely new way of measuring charge relaxation in materials. Along the way to developing this technique, I developed several new signal processing advances. I have convinced MIT to pursue a patent on one of these ideas.

Main projects being pursued:

1) The study of quantized states in semiconductor quantum dots and the study of traps and localized states in semiconductors.
2) The development of time resolved SECS for the study of "nonequilibrium" systems, and the creation of high speed SECS for the observation of fast electronic transitions.
3) Adding a scanning capability to SECS.
4) Utilizing single electron transistors for greatly enhanced signal to noise levels in SECS.

Review of the SECS technique:

In the simplest version of SECS, we position the small object of interest between the two plates of a "tunnel capacitor." Electrons may tunnel between the object and the "bottom" plate while a large barrier forbids tunneling to the "top" plate. By adjusting the voltage applied across the plates, single electrons are caused to tunnel onto and off the object. Once the electron tunnels onto the object, image charge is induced onto the top plate. By building a high electron mobility transistor (HEMT) directly onto the "chip" containing the sample we demonstrated that we could detect and precisely measure this image charge.

In addition to applying a dc bias across the tunnel capacitor, we prompt single electrons to tunnel back and forth between the object and the bottom plate using

an ac voltage. We then synchronously detect signals due to electronic tunneling. Peaks appear in the response at those particular positions in dc bias at which a quantum state in the object is energy resonant with the chemical potential in the bottom plate. A simple geometric scale factor converts the dc bias scale into an energy scale for the object to allow a quantitative energy level spectroscopy. In essence, we measure the ground state energy levels of a system containing a specifiable number N of electrons as a function of an extrinsic parameter (e.g., magnetic field). The resolution of this technique is limited only by the sample temperature.

1 Traps created by disorder and impurities in Semiconductor Structures

Personnel: Ho Bun Chan, David Berman, and R.C. Ashoori
Sponsorship: ONR, JSEP, NSF, Packard Foundation

One system that we are studying in detail is a circular disk of electrons 1 μm in diameter and contained within a GaAs quantum well. We empty this disk and begin adding electrons to it. The first few electrons enter localized states of this disk. Observation of the magnetic field evolution of these energy levels allows a characterization of the type of minimum which localizes the electron as well as the lateral extent (localization length) of quantum levels. We find that some of the states are localized on minima of the disorder potential while others are located on *single* impurity atoms. At higher filling, the sample behaves as a disk of two-dimensional electron gas (2DEG), with Landau level structure evident in magnetic field.

Another type of sample that we are studying is a "pure" quantum dot in which electrons are localized in one lithographically defined trap. Of chief interest here is the role of the electron-electron interaction in modifying a dot's electronic level structure. Single-particle-like states exist in the limit of very small dots, while level structure is dominated by the electron-electron interaction in larger dots. Since the confinement potential in semiconductor quantum dots can be controlled at will, there exists a continuum of physics that we may explore. We plan a detailed examination of quantum dots in different size regimes.

While our previous SECS data were taken in a helium-3 refrigerator, we now have the capability of cooling samples down in a dilution refrigerator (at below 30 mK). As the transistor used in the SECS measurements is mounted directly on the sample, we must use very low transistor power in order to avoid heating the sample. We now stage several transistors for our measurements. The power supplied to the transistor on top of the sample for our present measurements is now less than 1 μW, and an electron temperature below 80 mK is maintained in the sample.

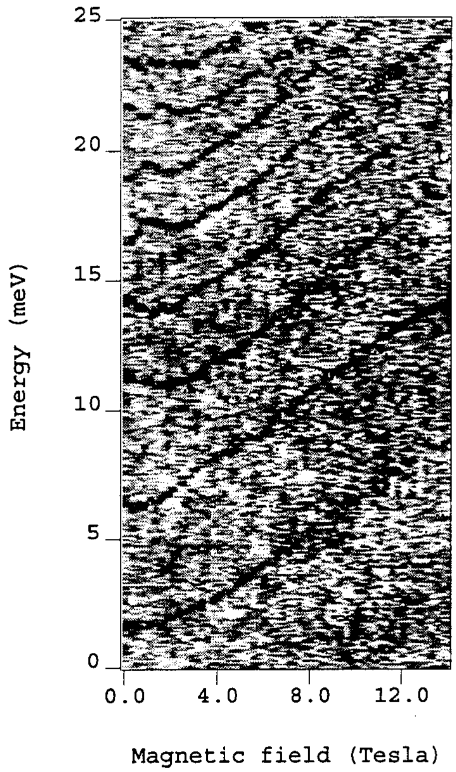

Fig.1 Initial SECS study of an artificial atom in the dilution refrigerator.
The bottom trace corresponds to the first electron in the artificial atom.

Figure 1 displays initial data on a quantum dot sample. The black traces represent quantum levels evolving in magnetic field. The traces shown are for the first 10 electrons entering a quantum dot. While the signal to noise ratio in this preliminary experiment obviously requires improvement, the extreme narrowness of the traces (a factor of 5 better in resolution than previous experiments) attests to the low temperature of the sample. For two electrons in the quantum dot (second trace from the bottom of the figure), the singlet to triplet crossing can be readily seen.

The signal to noise ratio seen in this experiment is limited by the input capacitance of the HEMT transistor. A large component of this capacitance is that of a 20 MΩ thin film resistor that we must use to bias the input of the transistor. We plan to replace this resistor with a tunnel junction. This should improve the S/N by a factor of 5. This will be the first step to replacing the HEMT transistor itself with a single electron transistor (SET). The SET should give a factor of 100 improvement.

2 Time resolved SECS

Personnel: Ho Bun Chan, Ilya Sokolinski, and R.C. Ashoori
Sponsorship: ONR, JSEP, NSF, Packard Foundation

Until the present SECS has been useful for studying the electronic ground states of various systems. It has provided little information on excited states. The technique has relied on the inducing electron tunneling by applying a small sinusoidal voltage and observing the signal that develops when an electron tunnels synchronously with the sine wave. The electron tunnels between states that have very nearly the same energy. If the amplitude of the sine wave is increased, more energetic states can be accessed. Unfortunately, the energy resolution of the technique is diminished (signals are blurred) with increased sine wave amplitude.

Rather than using sine waves to induce electron motion we now use sudden voltage change to induce tunneling, and we watch in real time the electron tunneling in response to this voltage. Using this technique, we can achieve high resolution spectroscopy of excited states. We observe changes in the tunneling as a function of the voltage step height. The scheme is also ideal for observing nonlinear relaxation in many types of samples. As an initial experiment, we have used the method to study tunneling from a two-dimensional electron gas in a "tunnel capacitor."

As one might imagine, data collection proceeds in a fashion rather different from typical synchronous detection schemes (such as with a lockin amplifier). The problem is to rapidly take and average many time domain traces. Typical digital oscilloscopes are not adequate for this purpose. Parallel processing of signals must be employed in order to achieve reasonable data rates. We have been using a newly (commercially) developed signal averaging system for this purpose. We have done significant work to customize this signal averager for our repetitive stimulus-response measurements.

All digital data acquisition systems generate some "cyclic" or "synchronous" noise that is synchronous with the triggering of the system. Typically, this noise is at the level of 1 part in 1000 of the full scale range of the system. Since our signal to noise levels are extremely poor (frequently the signal level is 1/100th the noise level!), signals must be average many thousands of times, and the system gain must be set low enough so that the noise does not overload the data acquisition system. The problem is that after signal averaging, the cyclic noise is larger than our signal!

I have devised a method for removing this cyclic noise, and it has worked very successfully. We now observe signals with details smaller than 1 PPM of the full scale range of the system! I have convinced the licensing office at MIT that this idea merits the pursuit of a patent. I will send the ONR a copy of the patent application once it is complete.

3 Spatially Resolved Charge Sensing

Personnel: Sven Heemeyer and R.C. Ashoori
Sponsorship: ONR, JSEP

We are presently developing methods for adding spatial resolution to our charge sensitive measurements. We are developing a charge sensitive scanning tunneling microscope (STM) for low temperature studies.

The basic idea here is to develop a scanning single electron capacitance spectroscopy. The method will allow for both the study of charge motion underneath surfaces and on the surfaces of insulators. If successful, I believe it will greatly enhance the utility of STM.

As a first step, we have recently completed building a room temperature STM. This STM is a "walker" design. Its chief advantages are that it allows large lateral range of motion in observations of the surface of a sample, and no mechanical linkages to the sample are required. Figure 1 presents room temperature data of a gold <111> surface. The lateral dimensions are 100 Angstroms, and the observed steps are about 50 Angstroms high.

We are presently constructing a low temperature STM. It will operate inside our helium-3 refrigerator at a temperature of 0.3 K.

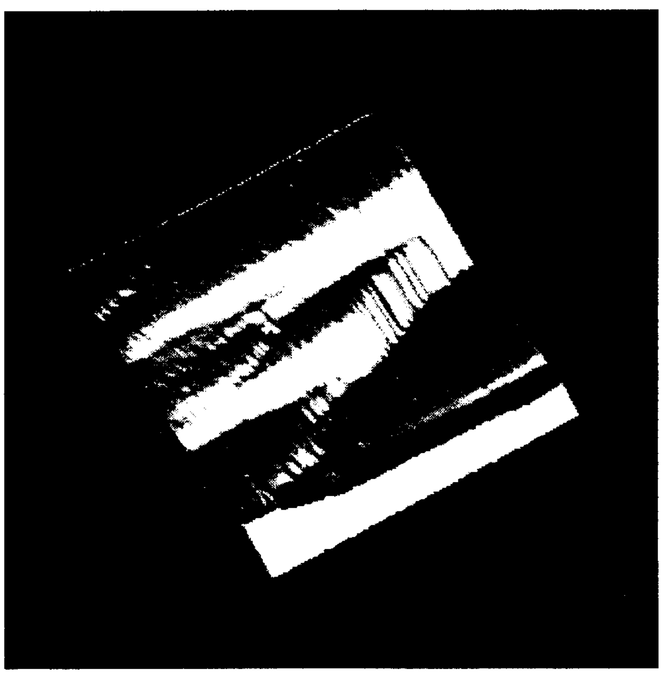

Fig. 2 Scanning tunneling microscope image of a Au <111> surface taken with our home-built scanning tunneling microscope.

The lateral dimensions are about 100 Angstroms, and the terraces are nearly 50 Angstroms tall.

4 Single-Electron Transistors for Spectroscopy

Personnel: David Berman and R.C. Ashoori
Sponsorship: ONR, JSEP, NSF

We are developing "single-electron transistors" to improve the sensitivity of SECS. Invented about 5 years ago, much excitement has focused the on the study of the physics of the devices themselves. With further development, these transistors hold promise as being the most sensitive electrometers available. Calculations indicate that they could provide one or two more orders of magnitude improvement in charge sensitivity over our HEMT's. Such sensitivity will greatly enhance SECS and will facilitate a number of experiments that are presently impractical.

We have converted an existing JEOL 6400 scanning electron microscope for use in electron beam writing. Using this system and the processing facilities of the Center for Materials Science, we have recently created our first single electron transistors fabricated from aluminum and aluminum oxide. We are presently attempting to integrate these devices onto semiconductor structures.

Publications:

Ashoori, R.C., Stormer, H.L., Weiner, J.S., Pfeiffer, L.N., Baldwin, K.W., and West, K.W, "Energy Levels of an Artificial Atom Probed with Single-Electron Capacitance Spectroscopy," *Surface Science,* **305**, 558-565, 1994.

Ashoori, R.C., Stormer, H.L., Weiner, J.S., Pfeiffer, L.N., Baldwin, K.W., and West, K.W, "Energy Levels of an Artificial Atom Probed with Single-Electron Capacitance Spectroscopy," *Coulomb and Interference Effects in Small Electronic Structures,* D.C. Glattli, M. Sanquer, and J. Tran Thanh Van, Editors, pp. 319-338, (1994)